LNG Interchangeability: Large Frame and Utility Research

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Introduction

Continued high natural gas prices, and little or no growth in dry gas production.

Domestic gas supply shows little variation in composition due to a fairly narrow range of supply sources

- Gas index variation +/- 2%
- Nominal 1342 (HHV) for US average
  - With some significant regional and seasonal differences

Continued expanded use of natural gas to meet growing demand for electricity.

Expected even greater demand for natural gas in world where CO_2 emission control, reduction, or taxes are emphasized as a solution for climate change.

Power Generation CO_2 Emissions

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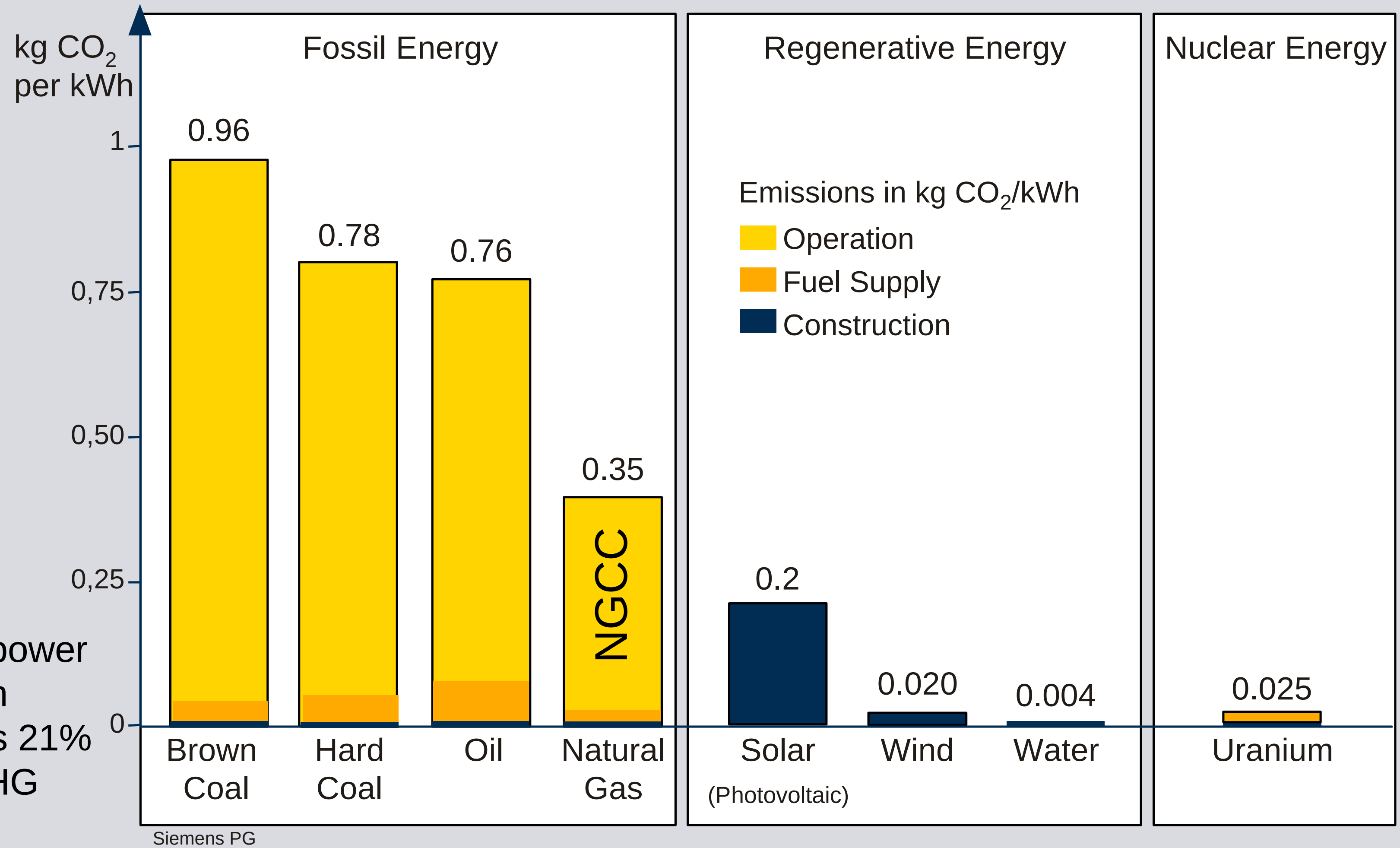


Globally, power generation represents 21% of total GHG emissions

Domestic Fleet: Large Frame Gas Turbines

Thousands of gas turbines have been deployed for power generation as well as pipeline support and cogeneration.

As much installed base in gas generation as there is in coal generation

- Underutilized because of fuel prices

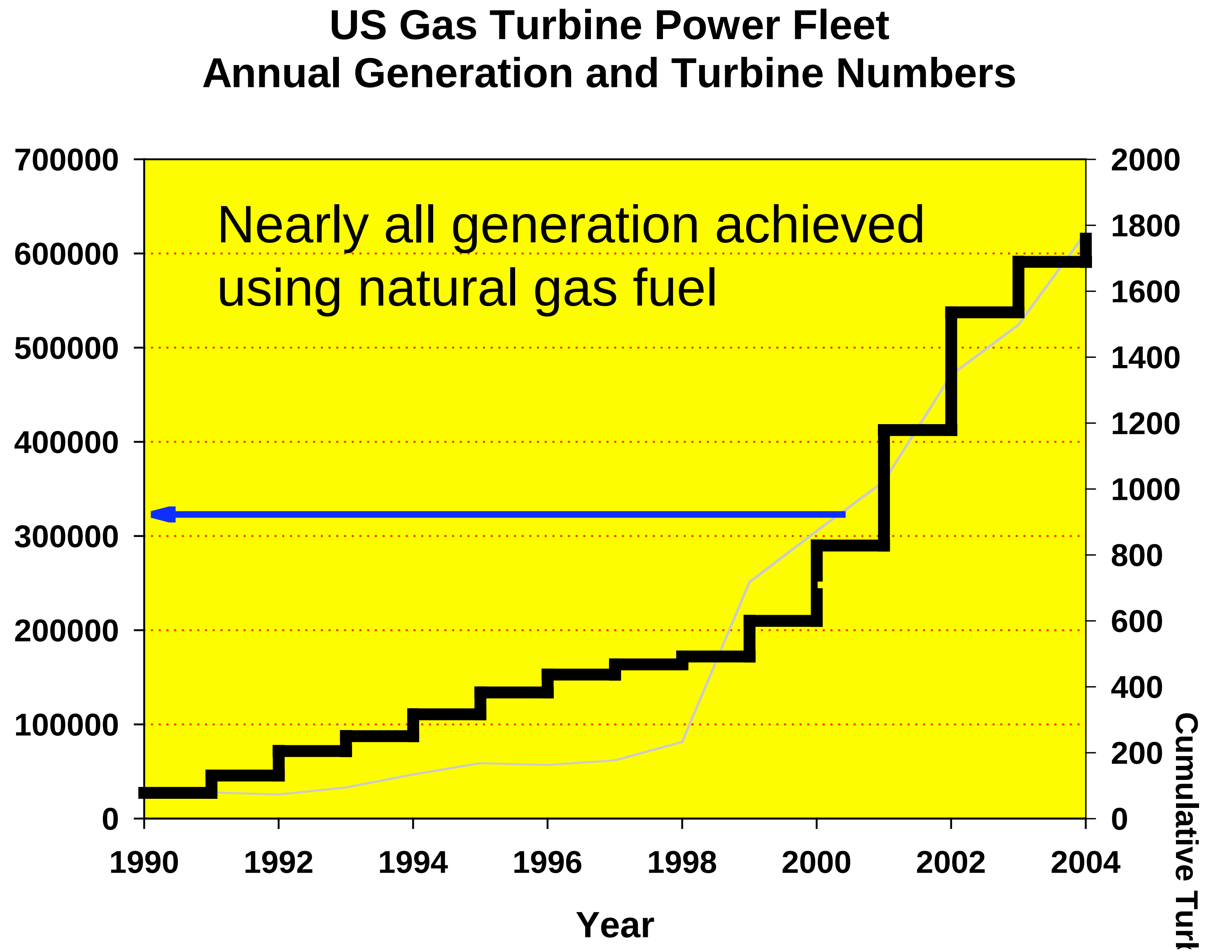
Cursory examination of the fleet reveals

- **50,000+ MW installed with DLN systems**
- **60,000+ MW installed with DLN and SCR**
- **25,000+ MW installed with DLN and water injection**
- **<10,000 MW installed with water injection and SCR**

Vast majority of new installations are pre-mixed, DLN combustion systems.

US Industry Statistics

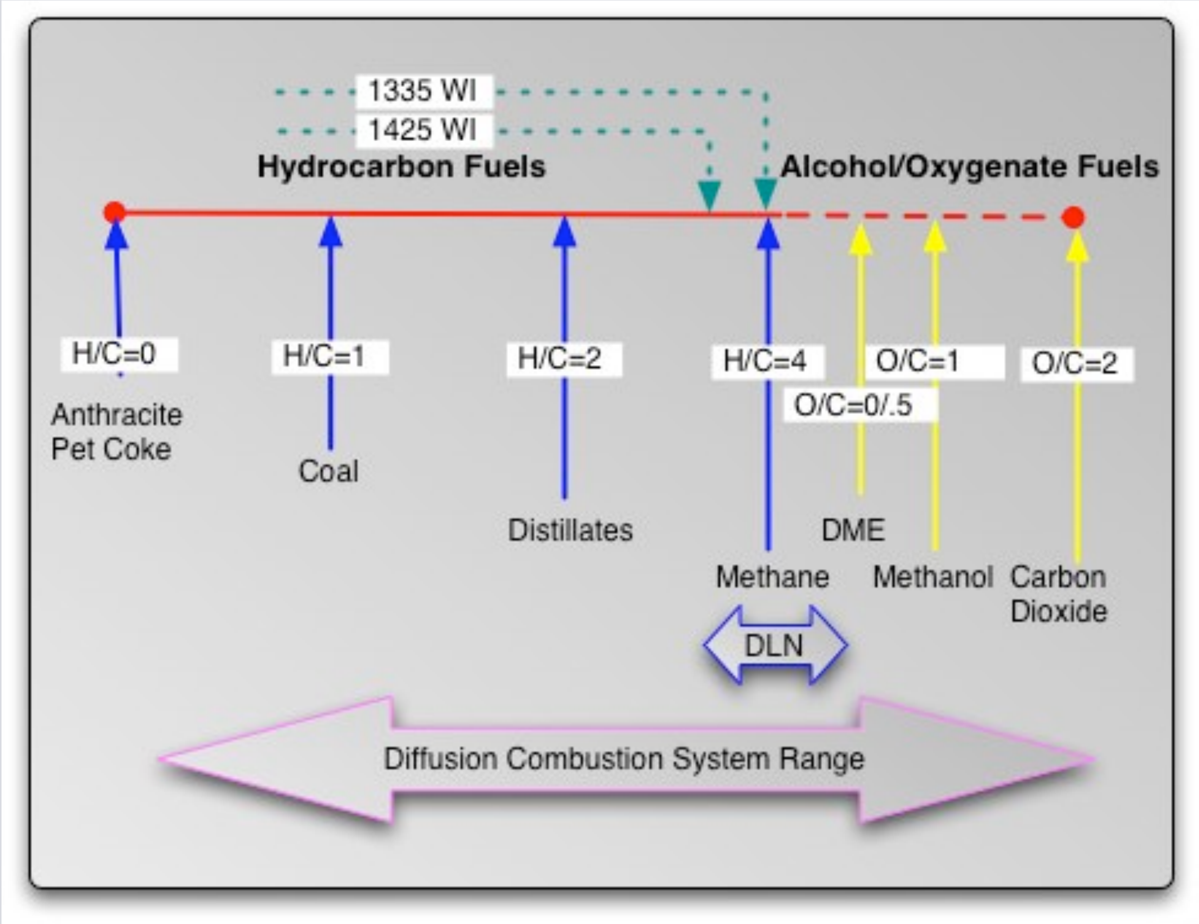
Data for gas turbines >50 MW in size



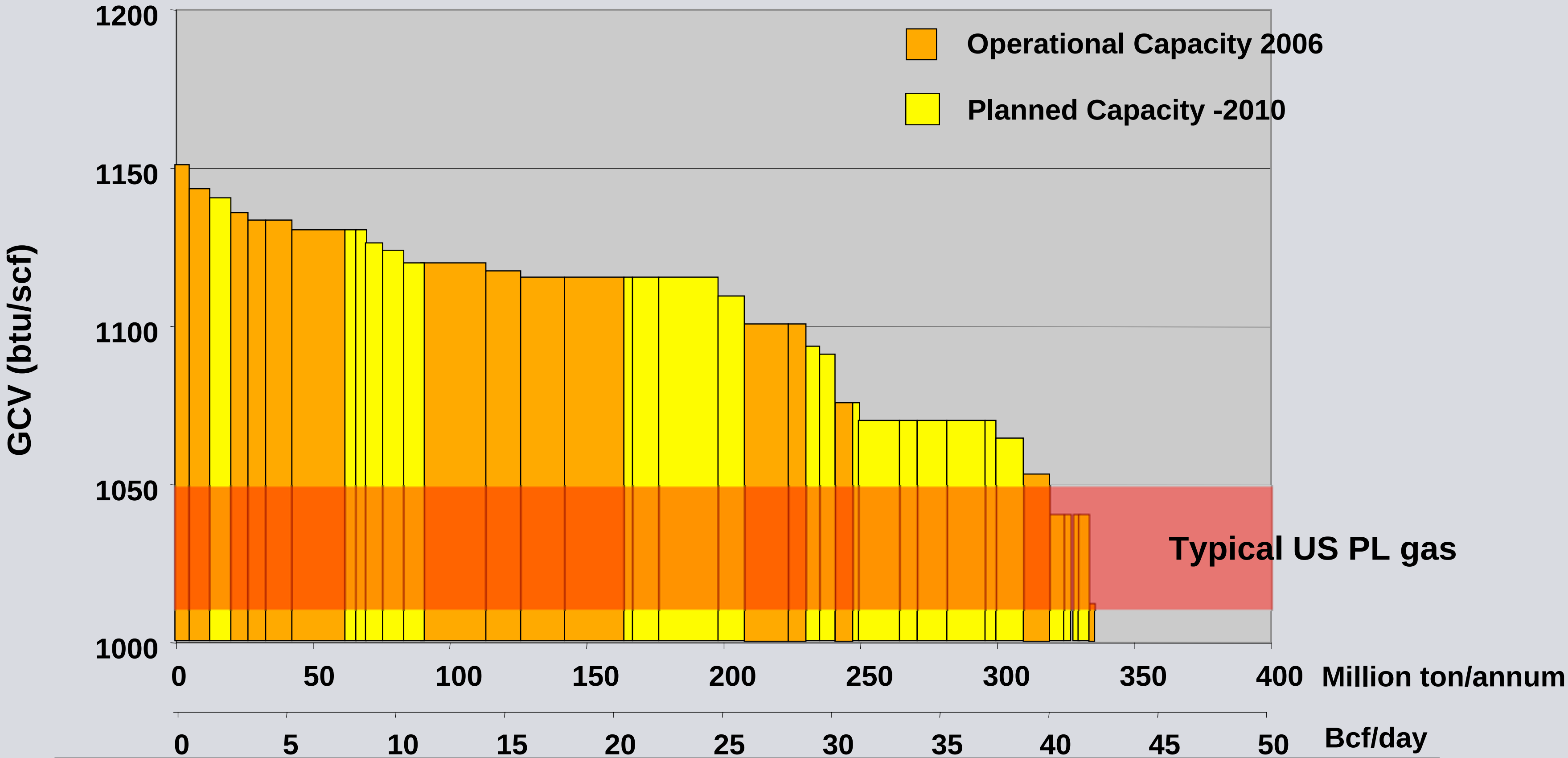
Fuel type makes a difference

Premixing fuel-and-air places unique requirements on the fuel and its basic chemistry.

DLN gas turbines are optimized to produce minimal NO_x emissions with a narrow range of fuel types.



Energy Content of Supplies



- LNG's have a higher Btu content than most pipeline supplies

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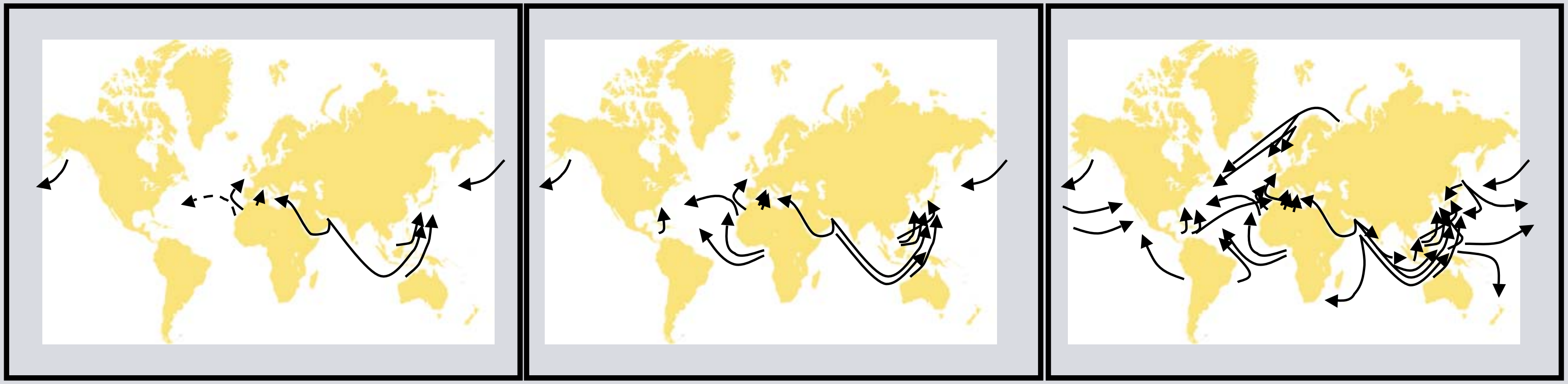
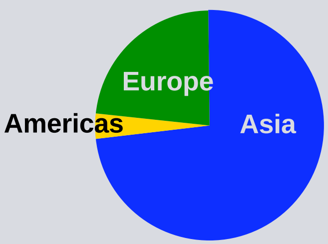
Add to this size and logistics of distribution

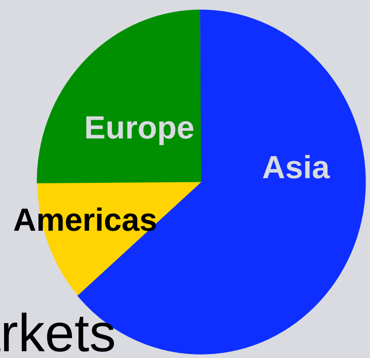


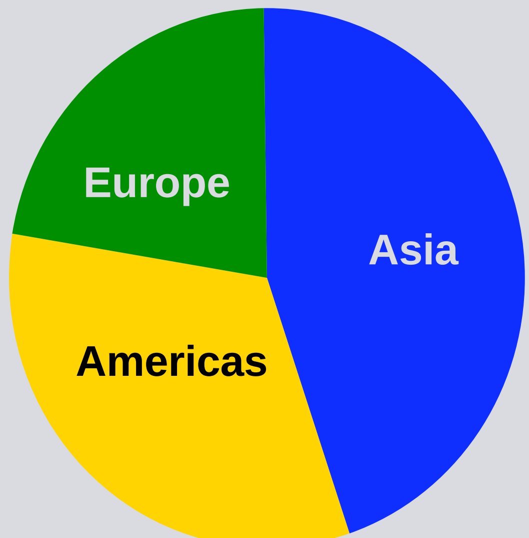
1990
56 mt
(4% of global gas)

2004
131 mt
(7% of global gas)

2020
~500 mt
(~15% of global gas)





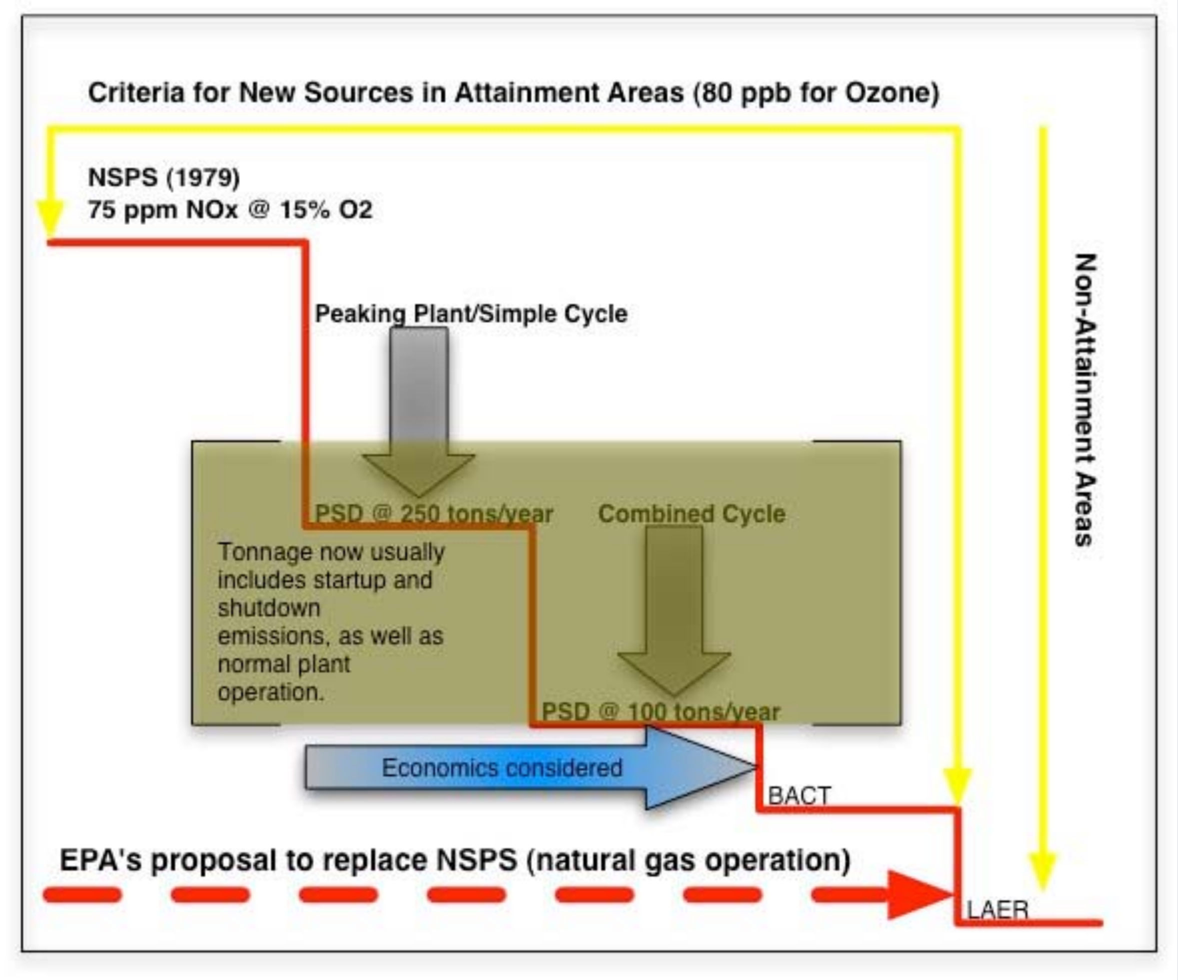


- from regional to global markets
- drive to diversify supply / markets

Facility size also makes a difference

Increasing size translates to greater mass flow of emissions.

To stay below PSD thresholds, there is an inherent push for lower emission concentration to counter siting restrictions



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How it looks at a multi-unit site

The total operating hours, plus the startup and shutdown emissions—for all three units—determine the total annual tonnage of emissions.

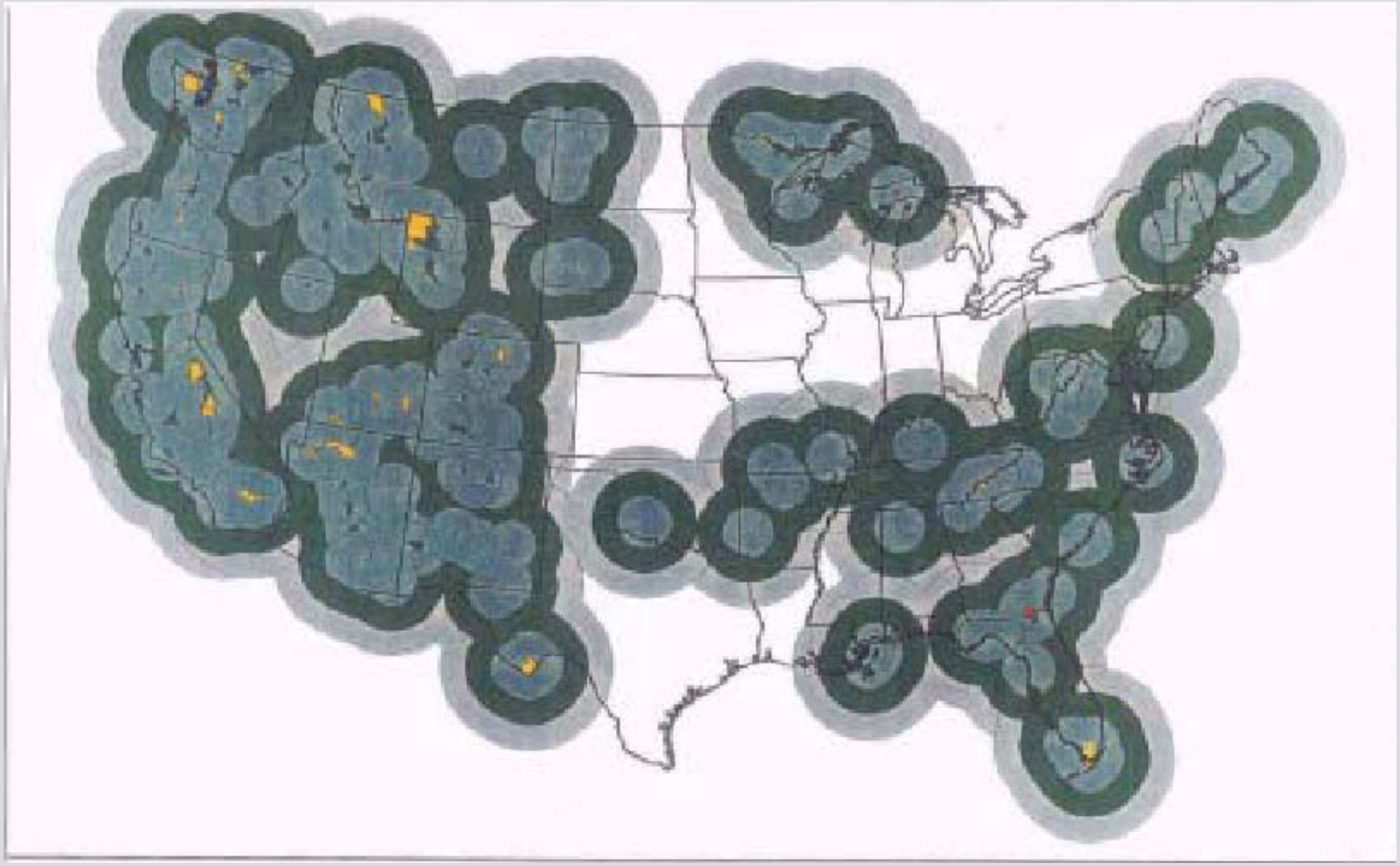
Each unit also has its own air permit with limits on concentration and mass emission rates (typically lb/hr).

Peaking Plant (F-Class Units) with SCR for NOx Control

Even location makes a difference

Each Class 1 area must account for new sources within 300 km radius.

Modeling of emissions from sources must account for the impact in the areas.



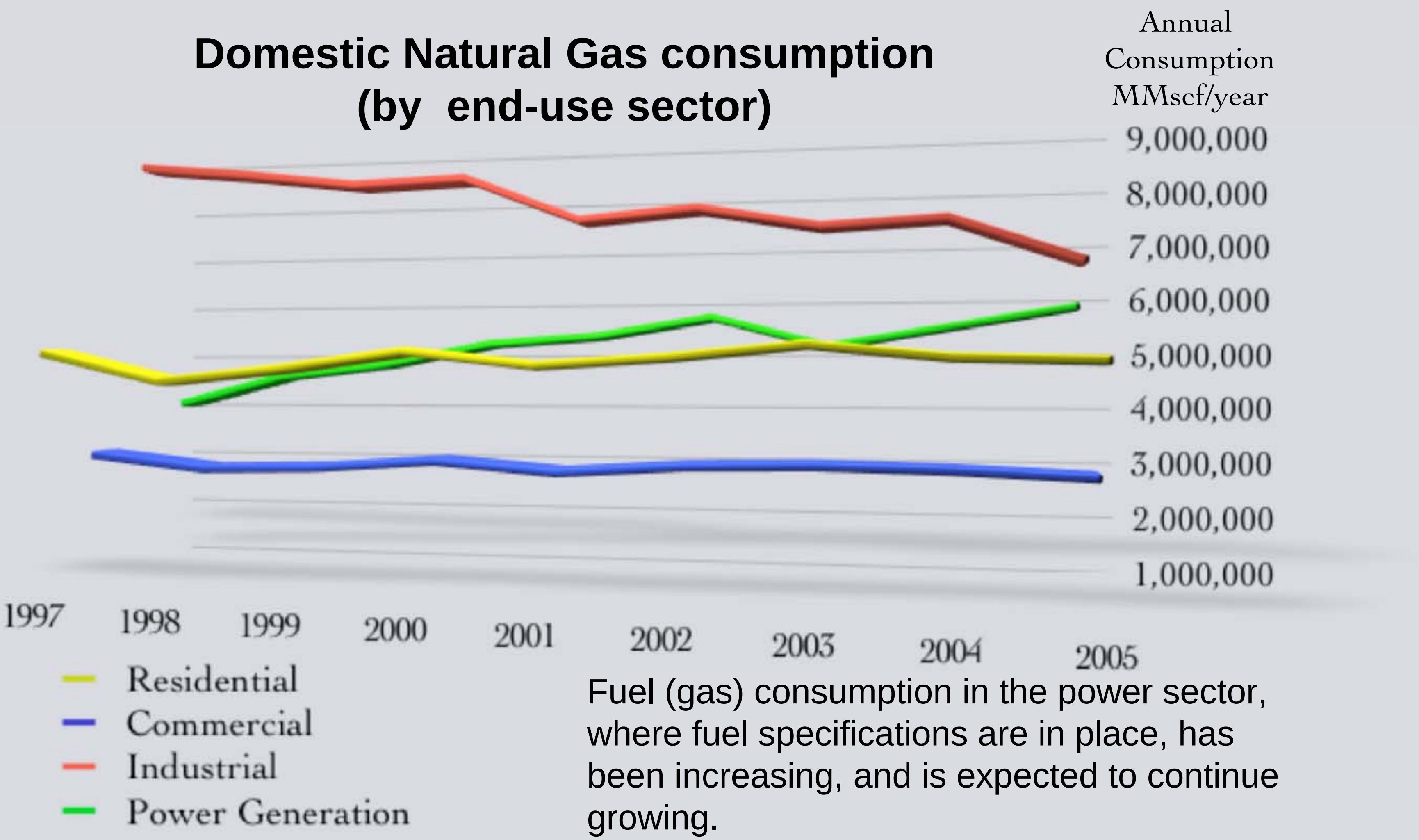
Complex Regulations are also a factor

Startup / Shutdown Emissions

- Large number of peaking plants installed raising concerns over startup shutdown emissions
  - DLN systems turn-down ratio is not as robust as the conventional diffusion combustor design.
    - **Significant departure from performance of steam coal units, steam gas, and diffusion combustion systems.**
- CO emissions are a significant factor during this period.
  - Significant on cold start/combined cycle.
  - GE 7FA emissions peak at about 800 ppm on the start cycle (lasting about 45 minutes)

Not a National or Federal rule, but usually shows up in the air permit

Natural Gas Fuel Consumption



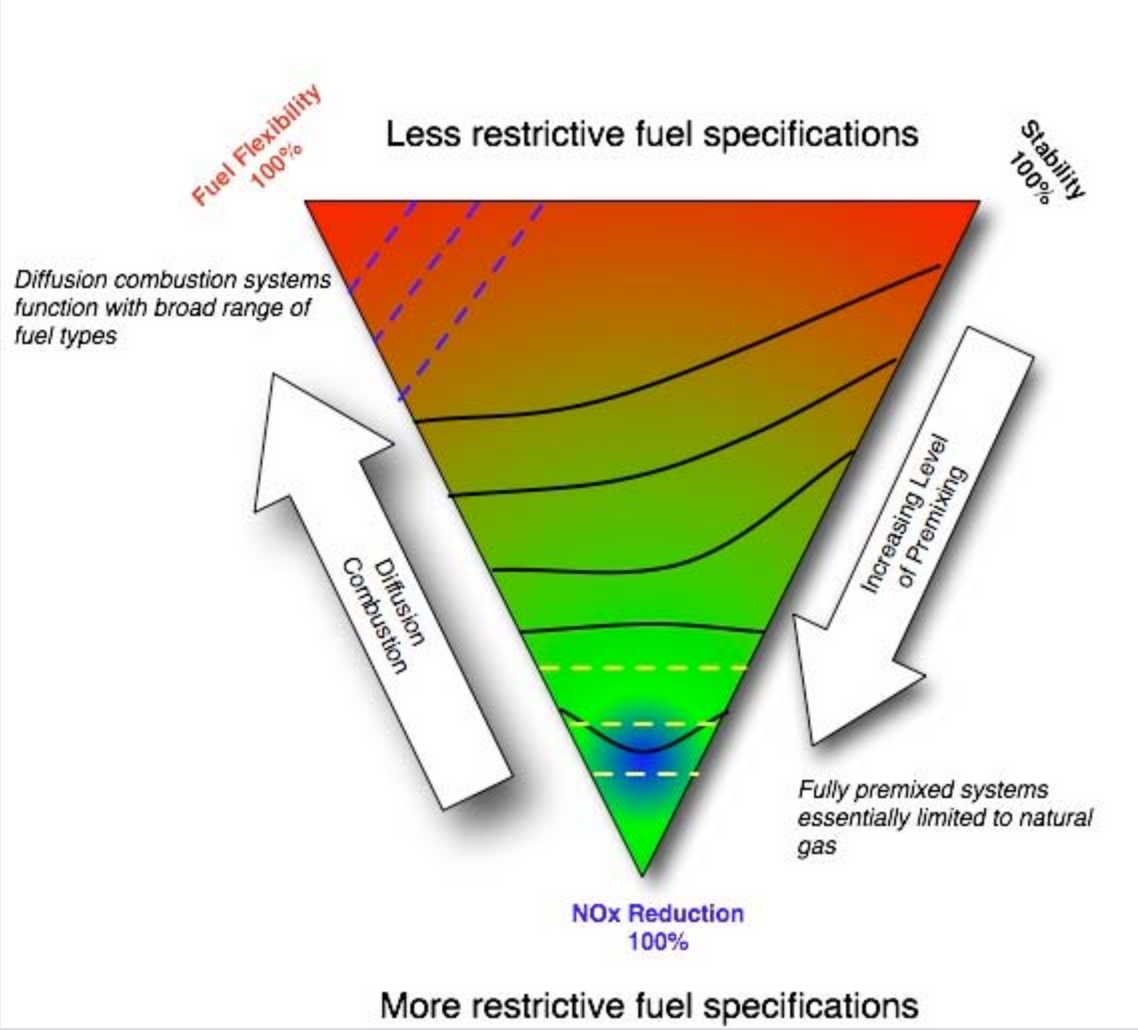
Fuel (gas) consumption in the power sector, where fuel specifications are in place, has been increasing, and is expected to continue growing.

Fuel flexibility is directly tied to combustor design.

- **Diffusion** flame combustor design
  - Highest degree of fuel flexibility.
  - Historically, the “safest” combustion design system for continuous burners
    - All aircraft gas turbines are based on diffusion combustor design.
    - Design of choice if fuel quality/properties are uncontrolled.
- **Premixed** design
  - Newest designs (DLN and DLE introduced in 1990’s)
  - Premix fuel and air introduced tighter requirements on fuel quality. These were necessary to control basic combustion process conditions:
    - Flashback, blowout, combustion instabilities, emissions, etc

Balance Design Criteria

Combustor design and fuel flexibility must trade-off different options. Focusing on a single element can compromise the performance in other key areas



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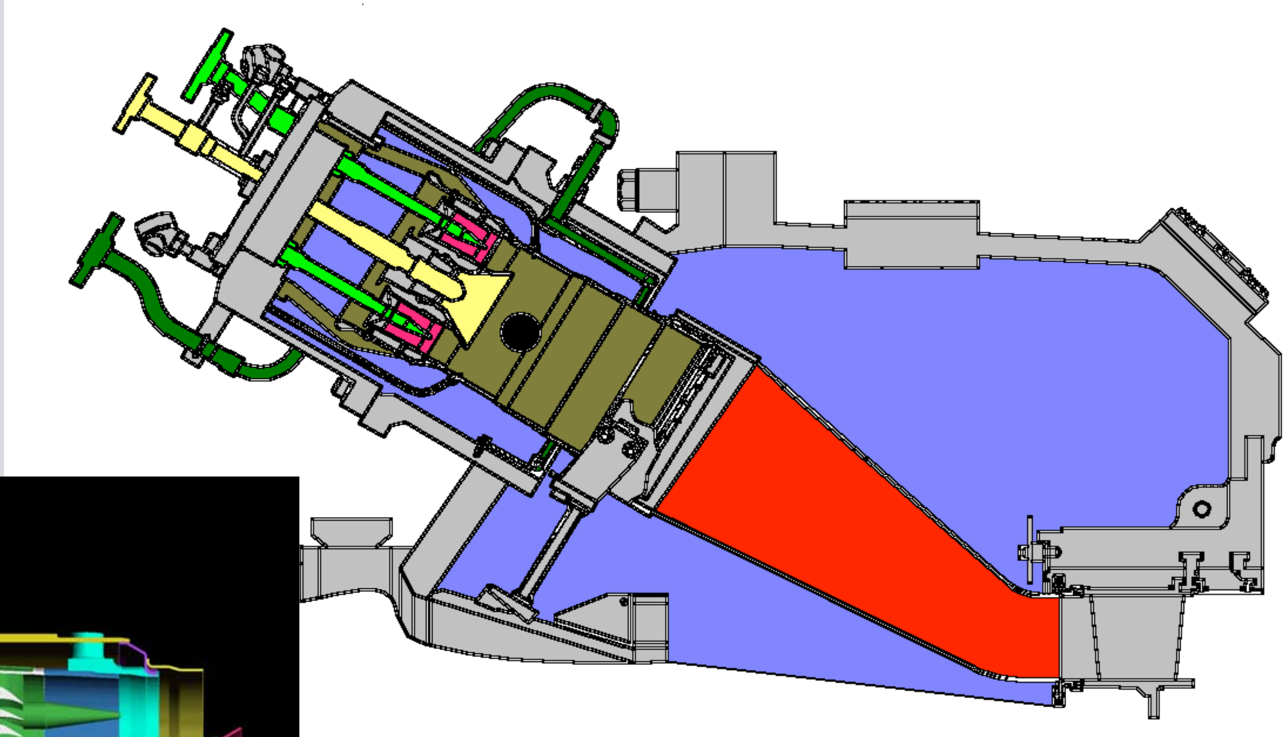
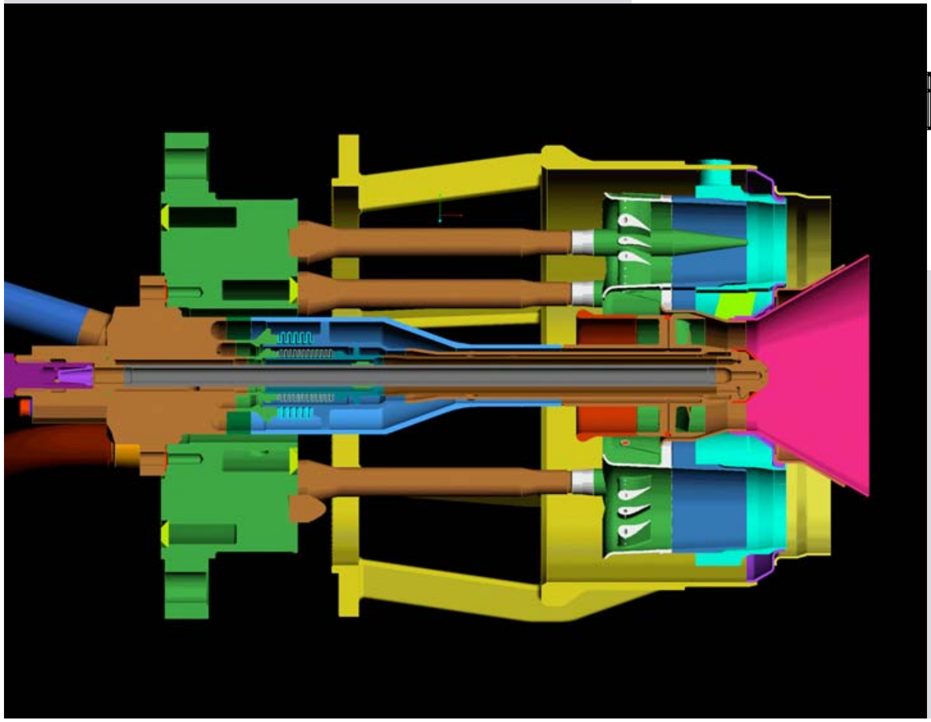
DLN (Premixed) Combustor

Required extensive research and development by both industry and government.

- Eliminated the need to inject a diluent (e.g. water) for control of NO_x
- Introduced additional requirements on fuel quality requirements
  - **Wobbe Index variability requirements are typically much narrower (15% vs. 5%)**
  - Limits on higher hydrocarbons to mitigate the risk of flashback in premixed systems.
- Premixed designs are predominantly natural gas (or based on gas fuels with very similar properties)
  - Much more difficult to substitute other fuel types into a premixed system optimized for a specific fuel gas

DLN Cross Section





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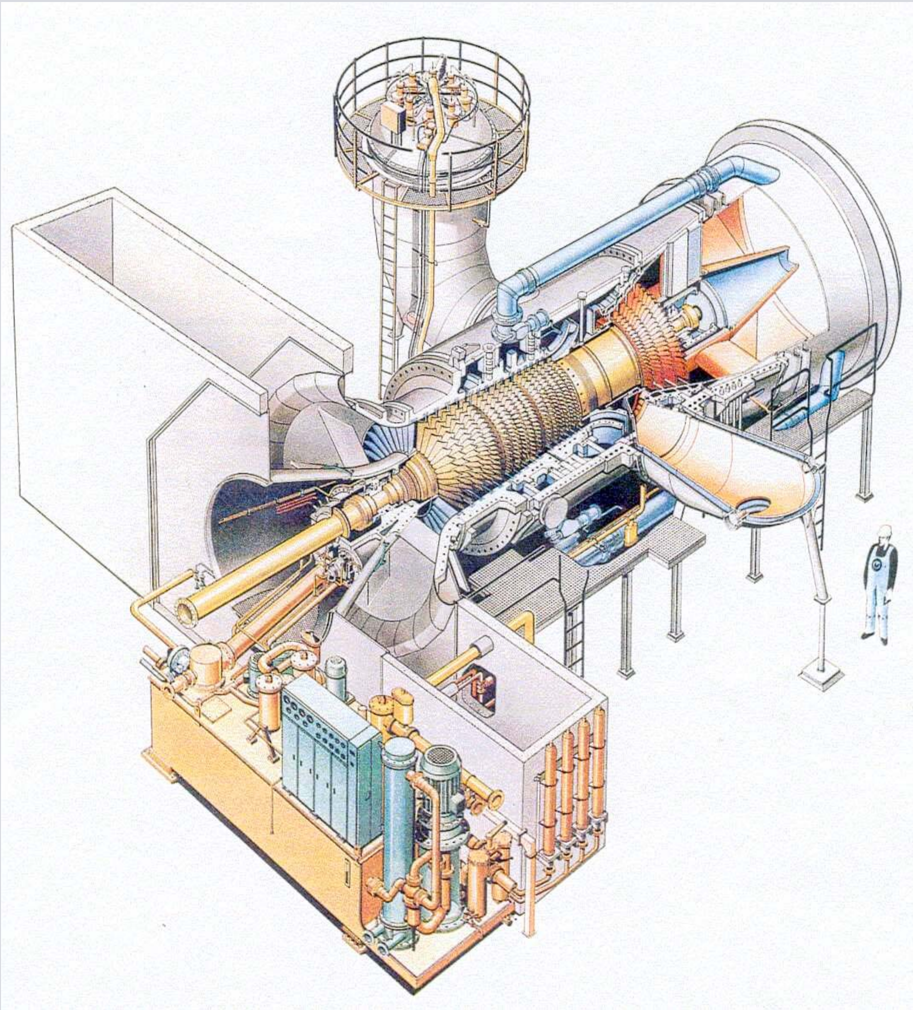
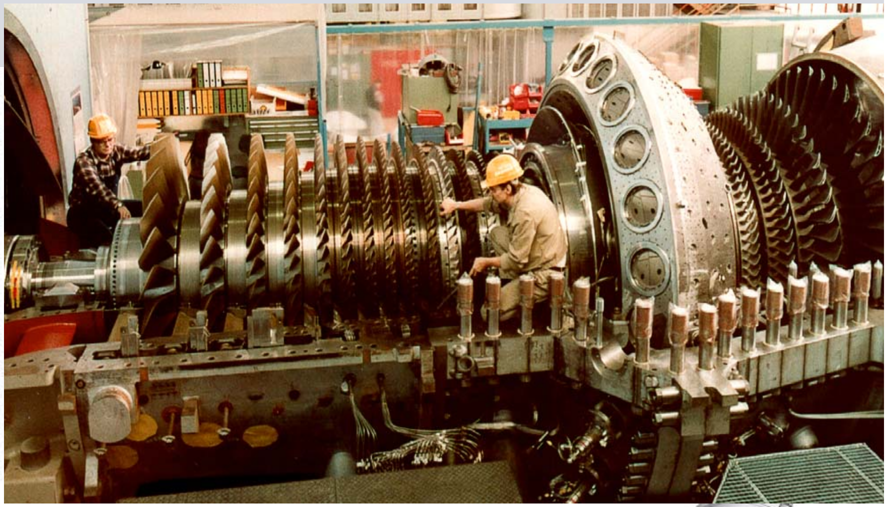
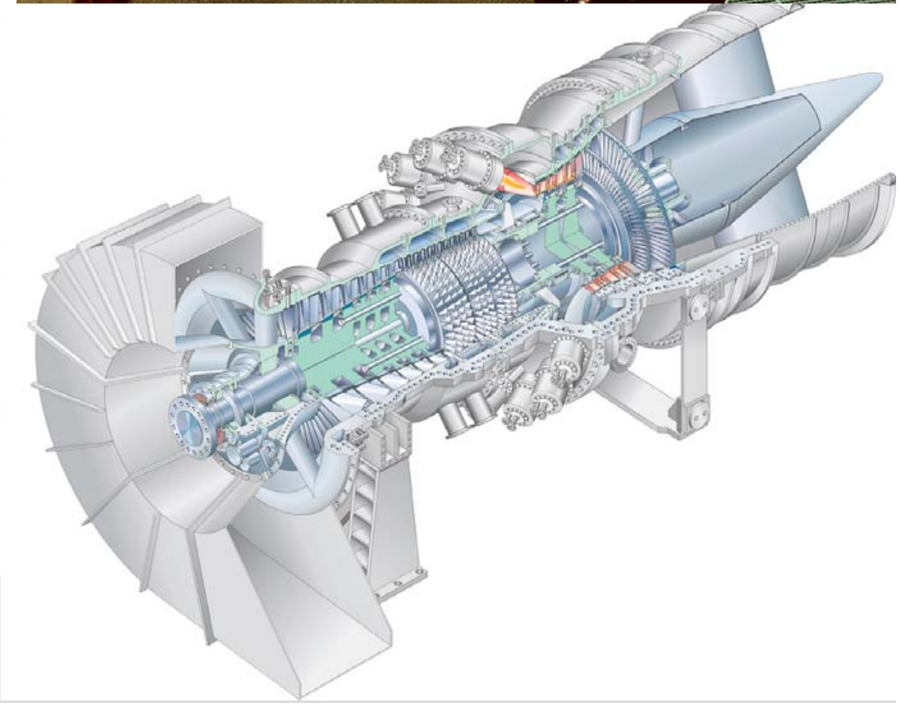
Gas Turbine DLN Designs







NGC+ Guidelines

- Interchangeability guidelines to FERC 2 March 2005:
  - Regional Wobbe range: +/-4% with respect to historic gas, subject to the following additional criteria
    - Maximum Wobbe Number of 1400
    - Maximum Heating Value of 1110 Btu/scf
    - Maximum Butanes+ : 1.5 mol percent
    - Maximum Total Inerts: 4 mol percent
- FERC Interchangeability Policy Statement - June 2006

  "*in negotiating technically based solutions, pipelines and their customers are strongly encouraged to use the Natural Gas Council Plus (NGC+) interim guidelines filed with the Commission on February 28, 2005 as a common reference point for resolving gas quality and interchangeability issues*".

Emissions-A New Emphasis

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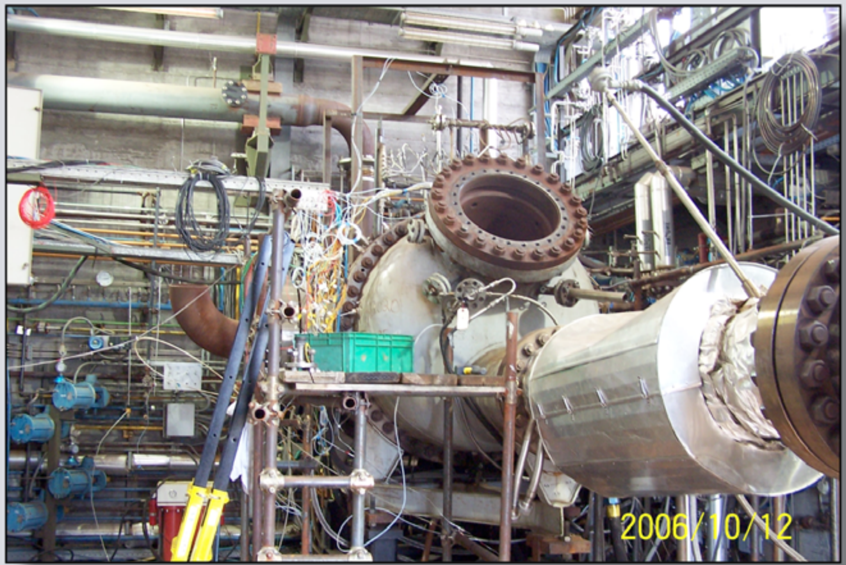
Fuel characteristics and combustor design both affect emissions

- Requirements for greater reductions in emissions (NO_x) have pushed engineering designs that require extensive use of premixed combustor designs
  - Which in turn sets new benchmarks, and limits, of specific fuel properties.

What are the basic properties of interest?

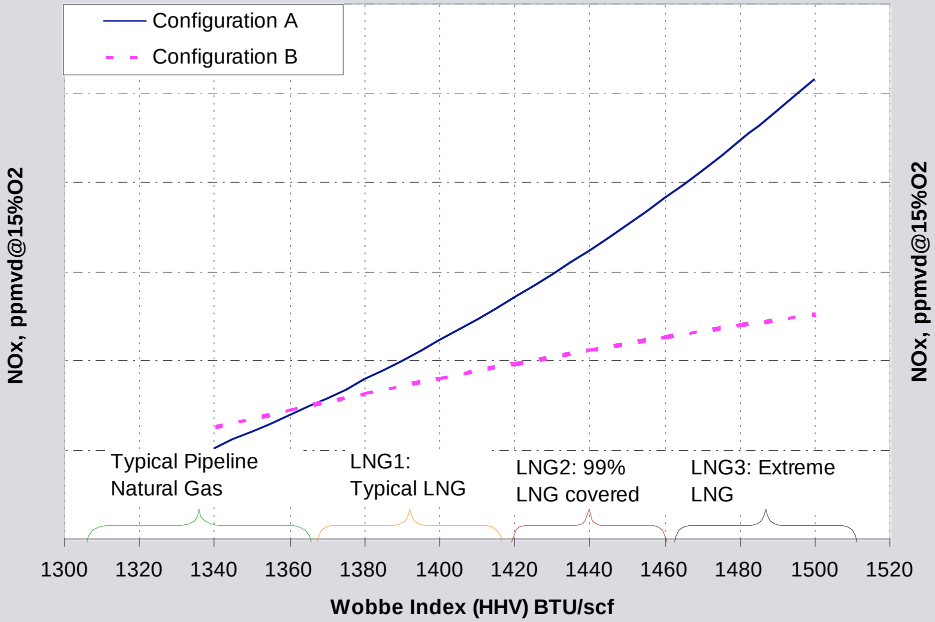
- Heating value (Wobbe Index), H/C ratio, diluents, dew point, fuel temperature, trace components (water, sulfur, particulates)
  - Basically those referenced in the NGC+ report
- Rate of change in these properties, which has typically never been specified.

LNG Rig & Engine Tests

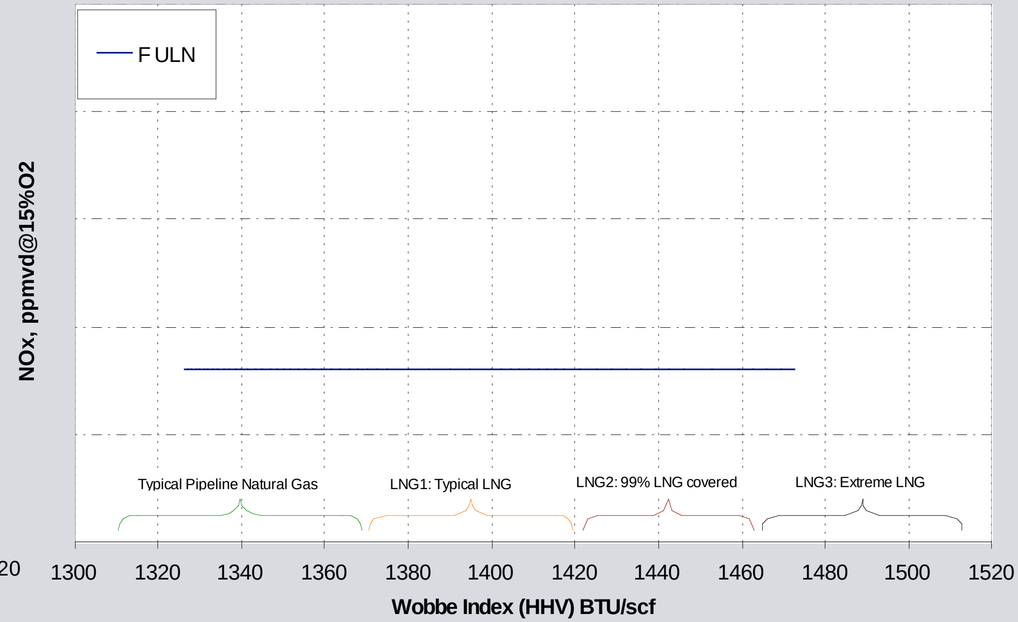


- ❖ Pure hydrocarbon fuels (ethane, propane, butane) mixed with natural gas (methane) in mixing skids to simulate LNG
- ❖ Tests performed in operating engine and high-pressure test rigs

DLN/ULN Test Results – F Class Gas Turbine



DLN



ULN

- ❖ NOx emissions increase with increase in Wobbe Index
- ❖ Configuration B significantly better than Configuration A
- ❖ Increased levels of heavy hydrocarbons beneficial to combustion dynamics
- ❖ Combustor can be ‘tuned’ to improve emissions performance
- ❖ ULN (Ultra Low NOx) system more robust to fuel constituent variations

DLN/ULN Test Results – D5A, F & G

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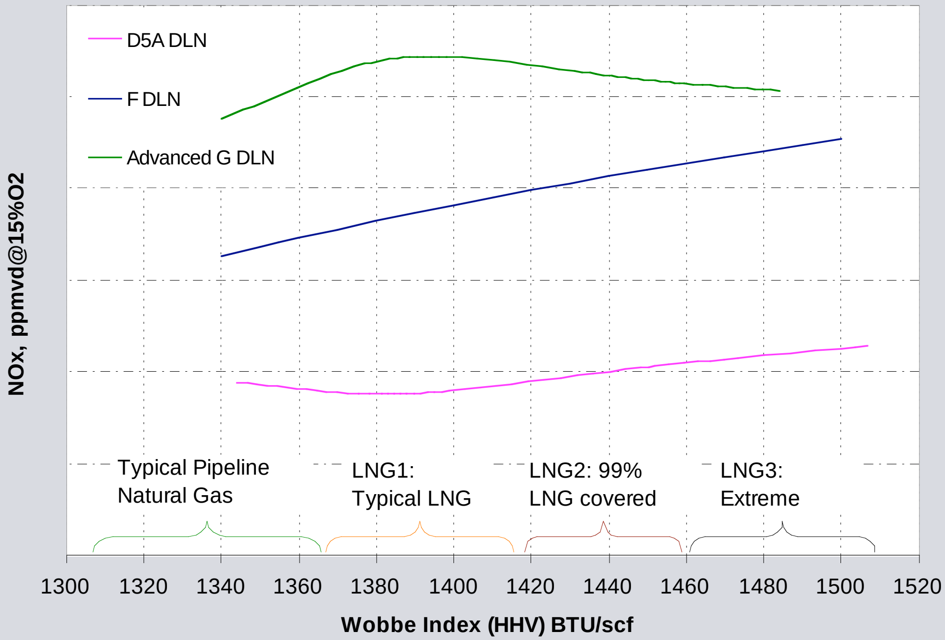
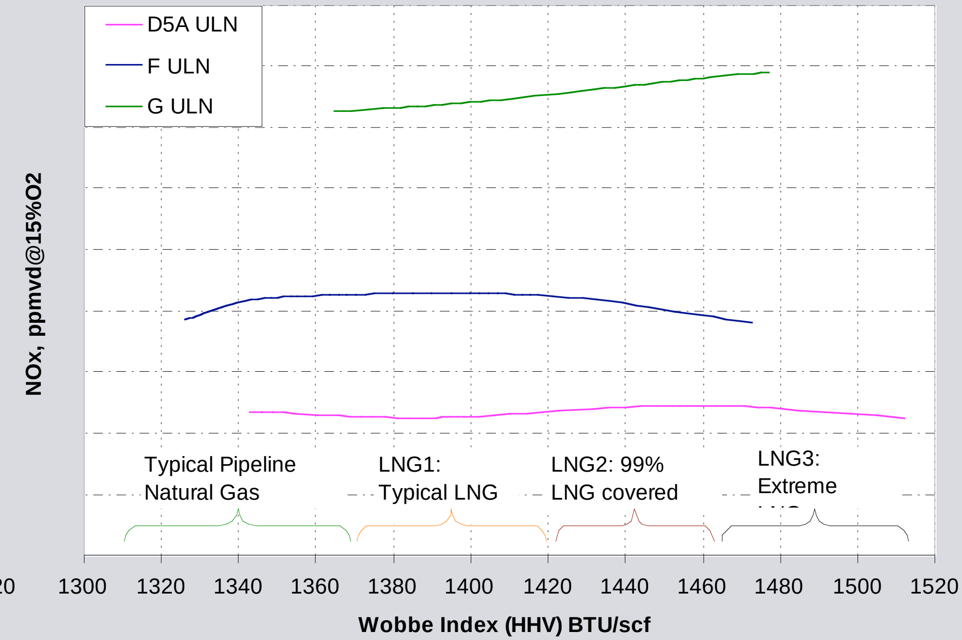




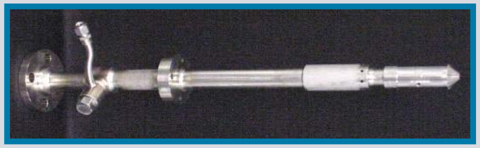
DLN

ULN

- Impact of LNG on NOx emissions within acceptable limits for all 3 frames
- ULN design less susceptible to wider constituent variations present in LNG
- Flashback margin acceptable
- No measurable impact on combustion dynamics with ULN

DLN Compared to ULN

DLN liner

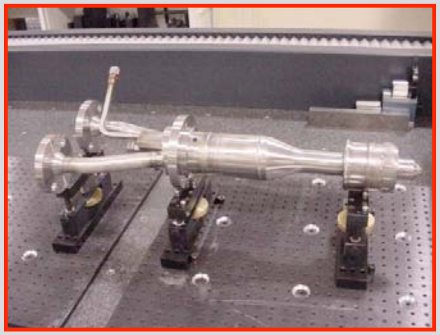


DLN pilot

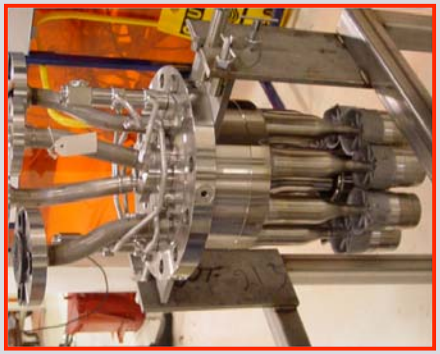
DLN A/B nozzle

ULN liner

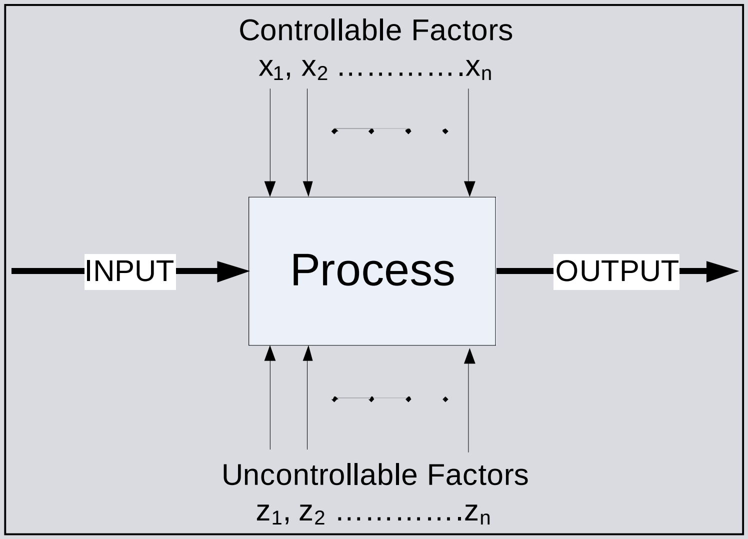
ULN pilot/D stage

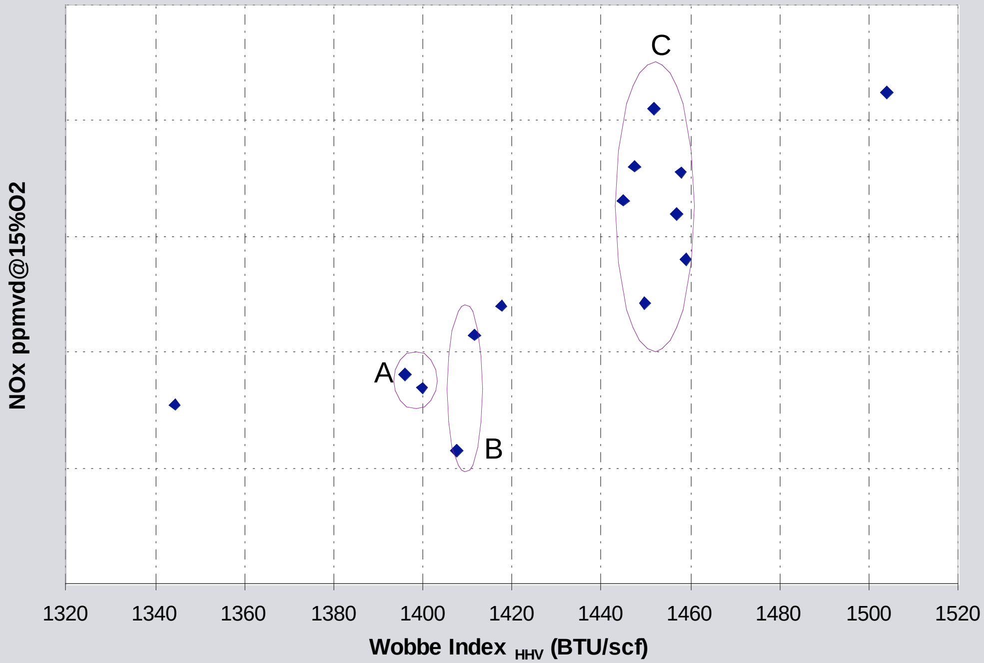


ULN A/B nozzle



Limitations of Wobbe Index
Design of Experiments (DOE) Study





- A statistically designed experiment (DOE) was used to understand the cause-effect relationship between the input & output variables
- Fuels with similar Wobbe Indices (A,B,C) but having different fuel compositions had different NOx emissions
- Wobbe Index alone could only explain 23.5% of the variation in NOx emissions
- 99.9% of the variation could be explained by the fuel composition (%C1, %C2, %C3, %C4 etc.)

Accommodating New Gas Supplies

Technical components that can be implemented, features that would broaden the fuel flexibility of the equipment. These would include:

- Active-Dynamic monitoring and tuning
- Fuel diagnostics and monitoring (to detect rapid changes to fuel properties before reaching the end user)
- Combustor design upgrades
- Fuel treatment (extraction, separation, blending, injection, heating, etc.)
- Post-Combustion controls (SCR, Ox-Catalyst)

Administrative actions to accommodate for change

- Establish center of excellence related to fuel quality and fuel performance
- Optimize decision making between energy supply and environmental objectives
- Resolve differences in tariffs and fuel specs (e.g. rate of change of Wobbe)
- Environmental policy should not set the pace for energy policy, and vice versa